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Monterey, California

MANAGING A COMMUNITY HOSPITAL BLOOD BANK WITH A FREEZER SYSTEM

by

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and

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The operational activities of a community hospital blood bank are described at all levels with special attention given to the inventory management of the bank. A distinguishing feature of this blood bank is the use of a centrifuge-freezer system which, prior to the ten day age limit, breaks down whole blood into its basic constitutents, and stores them for extended periods far exceeding the normal twenty-one day shelf

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life of whole blood. The inventory management policies thus include regulating the input of blood into the bank, the transfer of blood from the refrigerator to the freezer and the issuing policy of blood for various medical needs. Concomitant to these problems is the problem of forecasting demand. In addition to containing a descriptive model with all its complexity, this paper includes simulation study which compares the operational characteristics (shortage, wastage and cost) of the blood bank with and without the freezer system.

MANAGING A COMMUNITY HOSPITAL BLOOD BANK

WITH A FREEZER SYSTEM[1]

1. Introduction.

A vital problem in maintaining any community health care delivery system is that of providing an adequate supply of whole blood and blood constituents. Since blood is perishable, this task must be accomplished with a minimum of waste; a factor which is particularly important since it can affect public attitude toward affiliation with the blood bank. In most communities and large metropolitan areas, the Red Cross supplies from fifty to seventy-five percent of the total blood demand while the remainder is procured through hospital and commercial blood banks. Recent studies of blood banks have concentrated for the most part on inventory policies for whole blood in community blood banks and regional systems [6,7]. More recently, however, advances in medical and related fields have resulted in greater utilization of blood by increasing the inventory holding times through the freezing of components. In this paper we present a descriptive and simulation model and discuss the management and operation of a typical community hospital blood bank that has a frozen blood inventory capability. We shall focus attention on the blood bank for a particular community hospital.[2] The services for this hospital blood bank are currently being expanded to achieve a greater, if not complete, degree of self-sufficiency through the freezing and storage of blood constituents, such as plasma and red blood cells, and through efficient use of a blood donor registry.

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[1]This work was partially supported by the Office of Naval Research under Research Project RR014-07-NR-047-116.

[2]The Community Hospital located in Monterey County, California, is a 175 bed hospital with six operating rooms. It is one of two hospitals that serves a 129,000 populus.

The objectives of this report are to fully describe the operations of a community blood bank, to identify the control parameters and criteria for establishing management guidelines, and to compare the operating characteristics of the system with and without a freezer system. Following a brief synopsis of medical background in section 2, we shall summarize the operational perspectives in section 3. Here we describe the activities of operation of a blood bank and identify measures of effectiveness and various inventory policies that are common to most blood banks. A descriptive model of blood bank operations is presented and discussed in section 4, followed by simulation results in section 5.

2. Medical Background

Human blood is divided into eight categories according to types: A, B, AB, and O, and the dichotomy of Rh positive versus Rh negative. Table I contains approximate frequencies of these categories within the general population. These frequencies are in fact approximate since they vary among different ethnic groups, and therefore among different communities.

Table I. Frequency of Blood Categories

Category	Type	Rh Factor	Approx. Percentage
1	O	+	39
2	A	+	34
3	B	+	8
4	O	-	7
5	A	-	6
6	AB	+	4
7	B	-	1.5
8	AB	-	.5

Inventory regulation, largely determined by "experience", is complicated by this distribution of blood categories; but moreover it is complicated by the short shelf life of whole blood. Whole blood not transfused after twenty-one days may not be utilized for a whole-blood transfusion. Although whole blood is required in many cases where blood is needed, especially when blood loss is acute, there are a great many instances which may better be handled by using blood constituents. The use of packed red blood cells, for example, carries numerous therapeutic advantages. In fact, the use of whole blood can often be detrimental to the health of the patient, as is the case with certain heart patients [1,8].

Whereas whole blood legally expires after twenty-one days, many blood constituents may be stored for varying periods of time before expiration. These expiration times may be extended, however, by the freezing of constituents or components [1]. For example, platelets must be transfused within three days[1] from the normal liquid state while frozen plasma and cryoprecipitate may be stored for a year before use. We note, however, that whole blood cannot be frozen as such, but must be broken down into its constituents by a centrifuge. We are assuming that this must take place within ten days from the time of withdrawal from human donors.[2] Once frozen, the process of thawing consists of treatment with glycerine and washing which requires a total time of 20 to 30 minutes. Once blood constituents have been thawed, they cannot be re-frozen for use, and transfusion must take place within 24 hours. This additional handling and processing that is required when blood is frozen obviously results in greater costs. On the other hand, freezing and thawing offers definite advantages over ordinary banked blood and blood constituents. The long-term storage of red blood cells deficient in common antigens is important for transfusions to patients with antibodies to these antigens. In addition, the frozen red cells are valuable for patients with rare blood types. Without further expounding on specific therapeutic benefits inherent in the usage of blood constituents, it suffices to say that the treatment of the patient is enhanced when the transfused constituent is as specific as possible for the patients' needs. To this end, it is more desirable, though more costly, that there be ample inventory of blood constituents on hand. The actual costs for this are yet to be determined.

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[1]Platelets must be stored at room temperature in order for them to be used within three days.

[2]This assumption is based upon policy followed at the Community Hospital Blood Bank, and will vary among different schools of thought. For the purposes of this model, this assumption will be maintained, although other assumptions can readily be incorporated into the model. The authors acknowledge a referee for pointing this out.

3. The Blood Bank Sub-System

The goal of a health care delivery system is to provide high quality health care to the community being served. Though admittedly difficult, there are ways of measuring health care (see [4]) to determine the degree of such quality. Among the many components in this complex system, the blood bank is of utmost importance and the effectiveness of the system is highly dependent upon the ongoing operational activities within this sub-system. Before considering specific measures of effectiveness for the blood bank sub-system, it is appropriate to identify these activities.

3.1. Operational Activities

The blood bank activities may be divided into the three areas: scheduling, drawing, and inventory management. Scheduling consists of establishing donor hours and regulating appointments, creating and maintaining an efficient blood registry, and, in general, communicating with the community at large. Figure 1 shows the activities in the drawing area. All potential donors receive preliminary screening by questionnaire. Any further screening requires a blood sample and then, of course, the actual drawing. Paramedical and clerical personnel must be assigned and coordinated for these tasks.

Inventory management is the nucleus for all ongoing blood bank activities. Specifically, this area encompasses the following tasks:

1. Maintain an ordering policy for blood from the registry and the Red Cross (or other agencies).

2. Assign blood for scheduled surgery.

3. Allocate whole blood to be decomposed and frozen.

4. Maintain an issuing policy for frozen blood constituents.

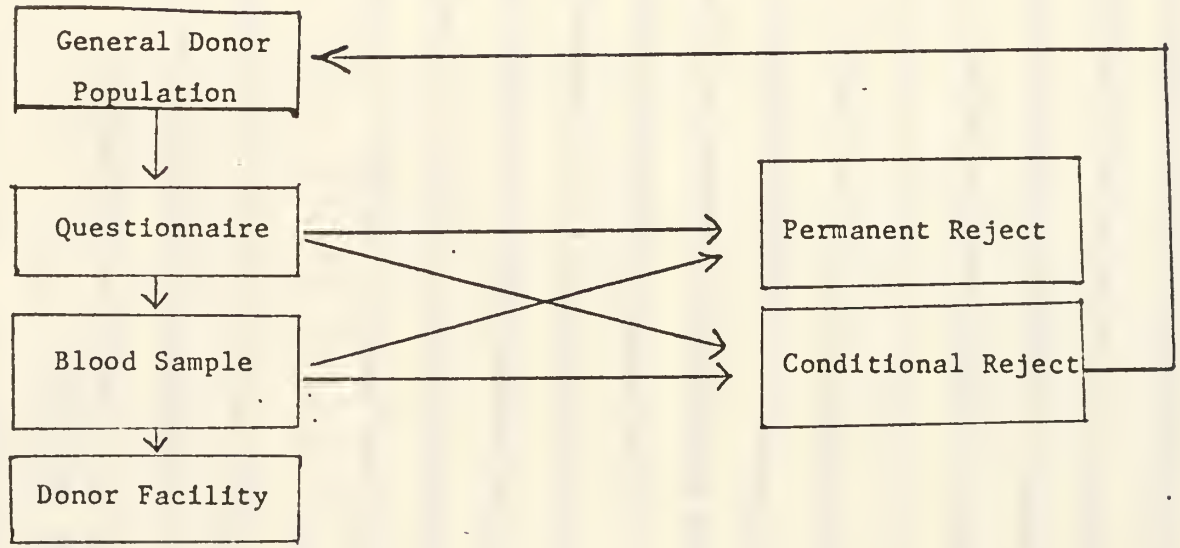

FIGURE 1. Management at the Drawing Level is summarized above. Conditional rejects, for example, often are potential donors with recent history of illness.

Concomitant to these tasks is the problem of forecasting demand, both for whole blood and blood constituents. The flow chart in Figure 2 summarizes the activities in the inventory management area.

After blood is drawn from a donor it is processed at some cost and then directed along one of the three routes: (1) to special surgery for immediate use (e.g. open heart surgery), (2) to be processed for freezing, or (3) to direct storage in the refrigerator. The decision to refrigerate blood in lieu of freezing is not irreversible: prior to becoming ten days old, blood may be sent along the centrifuge - freezer route. This allows the blood bank manager a sequential option. In fact, it is difficult to see why one would ever exercise the option to freeze blood prior to the ten day limit, since it would always seem optimal to defer commitments until absolutely necessary (see Figure 3). Likewise, a decision to use frozen blood constituents should be timely and firm since thawed blood expires beyond twenty-four hours and re-freezing blood is not allowed. Besides the ordinary output of transfusions and expirations from a blood bank, blood may also be sent from the freezer or refrigerator to other blood banks upon demand. In general, however, the use of other blood banks as a source of input should be limited to emergencies only. Planning otherwise could lead to both excessive costs and risk.

3.2. Measures of Effectiveness

The effectiveness of an entire health care delivery system is indeed multidimensional, and at the system level the primary performance measures are health care quality and, of course, costs. At the blood bank component level, which is of concern here, these measures are dependent upon two variables. The first is the number of shortages that occur over time. If the inventory for any category of blood, or blood constituent, is

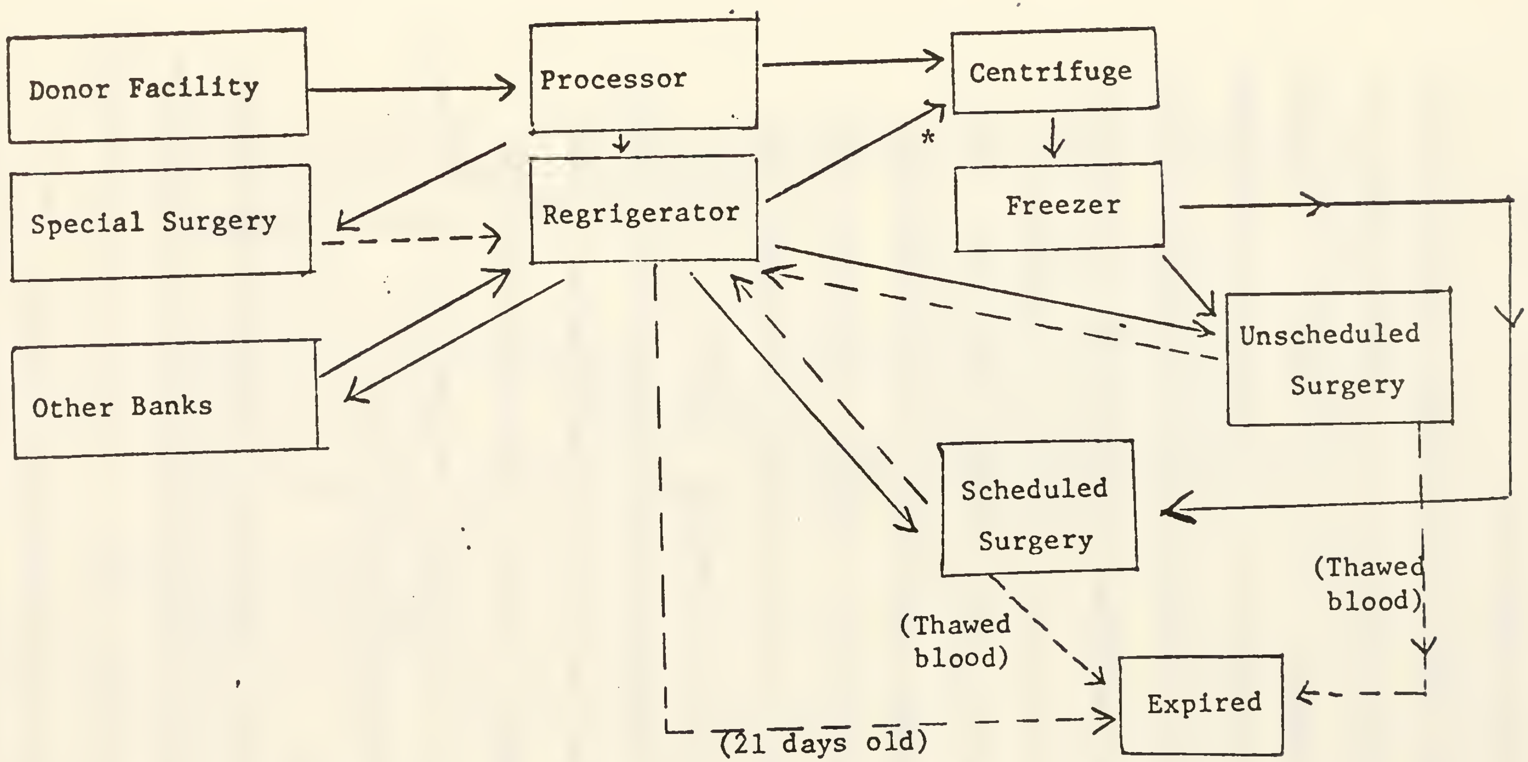

FIGURE 2. Inventory Management Flow Chart

Solid arrows indicate management control. Dashed arrows depict blood that is either expired or unused and returned to source.

*Must be within 10 days.

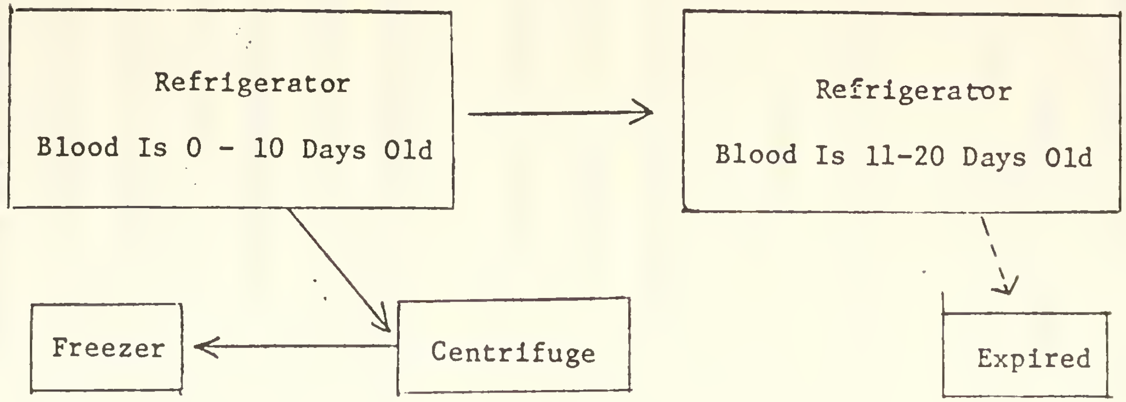

FIGURE 3. Flow chart describing the role of the freezer as a buffer preventing blood from expiring.

depleted at a point in time when a patient is in need of that category of blood, then the consequences are penalty costs incurred for instantaneous procurement from external sources, detrimentation to the quality of health care, and possibly both. The second variable is the amount of blood that expires over time, and it poses an indirect threat to health care quality as well as being an economic factor. Since our only source of blood is from human donors, it is important that the public attitude toward blood bank operations be favorable. Clearly, this would not be the case for a blood bank that has a reputation of having a high wastage of blood.

Thus the ideal blood bank is one that provides at a minimum cost an adequate inventory system to meet most demands, with shortages and wastage, through expiration, kept to an absolute minimum. It is difficult to simultaneously minimize all three of these variables because of the finite shelf life and uncertainty in demand of blood. Nevertheless, blood bank managers strive for the ideal by imposing various inventory policies.

3.3. Inventory Control Policies

Over time units of blood are demanded, ordered, assigned, and transfused. Typically, the number of units associated with each of these functions over time are random variables, but some smoothing is performed by inventory control. For example, although demands for blood occur at various points in time and at physically remote locations within a health care system, demands on the blood bank are mostly scheduled a day or so in advance with some unscheduled emergencies. There is still uncertainty in the actual amount of blood that will be transfused even though one knows that some blood will be needed. Thus, it is necessary for the blood bank manager to observe an inventory level, monitor and project the deviations between the amounts transfused and those assigned for scheduled demands, and predict and order the total amount of blood for an oncoming time period. Let $0 < t_1 < t_2 < \ldots$ be the time epochs where blood is re-ordered and for a particular category of blood, e.g. A+, let $T(t_j)$, $A(t_j)$, and $Q(t_j)$ correspond to the number of units transfused, assigned, and ordered, respectively, during the period $t_{j-1} < t \leq t_j$. Thus, the total inventory level is given by

$$I(t_j) = I(t_{j-1}) + Q(t_j) - T(t_j) - \epsilon(t_j) \tag{1a}$$

where $\epsilon(t_j)$ is the amount of wastage that is incurred during $t_{j-1} < t \leq t_j$, and the effective inventory level is

$$\tilde{I}(t_j) = I(t_j) - A(t_j) + R(t_{j-1}) \tag{1b}$$

where $R(t_{j-1})$ is the amount of blood that is returned from the assigned blood at t_j. Equations (1a) and (1b) are balance equations for the inventory system. When $I(t_j) < 0$, shortages occur and when $\epsilon(t_j) > 0$ there is wastage. In efforts to avoid these conditions the blood bank management refers to some equivalent of these balance equations and attempts to coordinate the allocation of blood units for each category optimally.

Blood bank inventory policies range in practice from total ad hoc procedures in small health care systems to computerized inventory control for regions [6]. These policies should include rules pertaining to the ordering of categories, order times and quantities, and assignment procedures. Jennings [3] found that for a large hospital the categories of blood may be treated independently. This, however, may not be the case for smaller hospitals. In a larger hospital, or health care system, it may be possible to order blood without specifying the amounts needed for each category. Smaller hospital blood banks may not be able to cope with the variability resulting from this policy; therefore, they must order by specific categories of blood. This latter policy will in general involve larger costs since more accounting is required. A third alternative is to utilize a mixing scheme whereby the order quantities of rarer categories of blood are specified while the others are not.

The ordering times, or more commonly "re-order points," may be fixed such as on a daily basis or they may vary with the inventory level. In general, fixed ordering times are most cost effective for blood banks. The variable order times occur whenever the inventory level $I(t)$ falls below some threshold level I^*. Note that in this case time is continuous. The disadvantage to this policy is that order times can fall at inconvenient times for placing orders, such as on weekends.

Perhaps the most common policy for order quantities is the classical $\langle s,S \rangle$ inventory policy whereby at each epoch t_j, if $I(t_j) \leq s$ then one orders up to level S, and otherwise waits until t_{j+1}. Tradeoffs between shortages and wastage have been described for this policy through simulation [2]. For some hospitals, depending upon the size and type, a modified $\langle s,S \rangle$ policy is employed where S varies with time. For example, a large teaching hospital may have surgery scheduled routinely on a particular weekday at which time the inventory level is required to be higher than that of any of the other days.

Pegels and Jelmert [5] described and compared two assignment policies. A modified FIFO (first-in-first-out) policy is one in which the probability of a unit of blood being transfused increases with its age, whereas for a modified LIFO (last-in-last-out) policy this probability decreases with age. Because of the finite shelf-life of blood, it is obvious that the modified FIFO policy would always be preferred to the LIFO policy.

4. A Comparison of Operations With and Without A Freezer System

A problem which must be addressed prior to the inclusion of a freezer system in a blood bank is that of quantifying the effects of such inclusion. In order to do this prior to the deed and without historical precedents, it is necessary to create a mathematical model upon which such a comparison may be made. Analytical and simulation techniques will give accurate quantitative measures provided the model assumptions are carefully validated. What follows in the remainder of this report is a detailed descriptive model of the decision and inventory-regulation process, and simulation results.

The random variables of significance to both the freezer and non-freezer models are:

1) The demand on each blood category for scheduled, unscheduled and special surgery (special surgery is defined as any surgery requiring blood less than 24 hours old).

2) The demands on each blood category from other banks.

3) The demands on blood constituents for scheduled, unscheduled and special surgery.

The decision variables of significance to the blood bank manager include the following:

1) Ordering blood (type specific) from the donor population.

2) Maintenance of inventory levels in the refrigerator (and freezer, including transferring blood from the refrigerator to the freezer).

When a freezer-system is in use, the manager also has the task of allocating blood constituents from either the freezer or refrigerator.

The random variables may be modeled and statistically validated, whereas the decision variables are difficult to ascertain -- especially in the case where a heretofore untried freezer system is to be used.

4.1. Model of The Demand

In a simulation study, it is both pleasing and acceptable to use historical demand data to form an empirical distribution function of daily blood demands. In this way inherent weekly and seasonal cycles may be included. The nature of the demand is so multifaceted, however, that it is very difficult to separate the component demand distribution functions from the overall one. In view of this and for the purposes of a simulation, we shall assume that the incidences of demand for blood on a given day (for emergency and special use that day or scheduled assignment the next day) form a Poisson process with rate λ. We emphasize that λ is the average number of demands for blood (whole blood or constituents) in a given day. Since in general the amount of blood ordered for a given patient is random, and may be assumed to be independent of other orders and incidences of demand, it is quite reasonable to view the number of units of blood demanded as forming a compound Poisson process. Provision is made in Figure 2 for unused blood being returned to the refrigerator.

In general λ depends on the day of the week and season. Although this dependence does not appear in the notation, it should be kept in mind and included in the simulation. To illustrate, since scheduled surgeries are often reserved for certain days of the week, one will naturally find that more blood is demanded for assignment on the day prior to a "scheduled surgery day." Seasonal variations are less profound and may be excluded. Also note that one unit of a blood constituent is defined as that amount found in a unit of whole blood.

The following conventions and notation are adopted:

λ_i = average number of demands for blood category i (whole or constituents) on a given day.

λ_i' = average number of demands on blood category i for emergency use on a given day. "Emergency" is defined as any demand that must be filled the same day.

λ_i'' = average number of demands on blood category i for assignment to scheduled surgery the next day.

λ_i''' = average number of demands on blood category i for "special surgery" (may be scheduled or unscheduled).

r' = the conditional probability that an emergency surgery is "special" (i.e. requiring fresh blood less than 24 hours old).

r'' = the conditional probability that a scheduled surgery is "special."

Thus $\lambda_i = \lambda_i' + \lambda_i''$, $\lambda_i''' = \lambda_i' r' + \lambda_i'' r''$, and $\lambda = \sum \lambda_i$.

The demand may conveniently be described by the chance forks of a decision tree (Figure 4). For a given demand, the probability is λ_i/λ that it will be for blood category i. The subsequent conditional probability that the demand is an emergency is λ_i'/λ_i. Thus the conditional probability (given category i) that a demand will be an emergency case, not special, and for plasma is simply $\lambda_i'(1-r')\hat{q}'\hat{\pi}_p'/\lambda_i$ where we let

π_p' = the conditional probability, given an emergency-nonspecial surgery requiring blood constituents, that the demand is for plasma.

π_c' = same, but for cryoprecipitate.

π_r' = same, but for red blood cells.

The presence of a $'$ indicates an emergency case, while a $''$ indicates a scheduled case. The presence or absence of the adjective "special" is

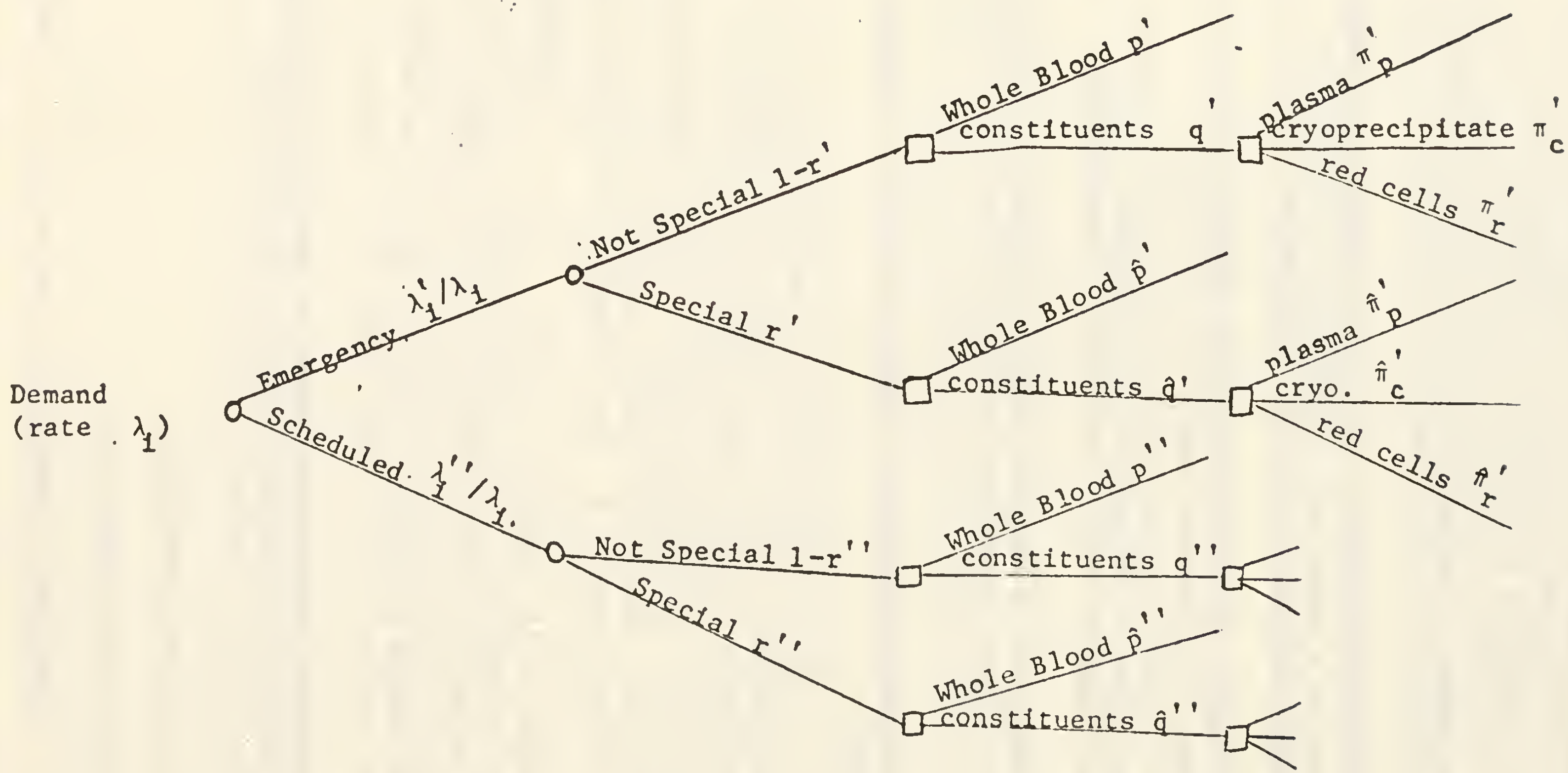

FIGURE 4. Initial portion of decision-tree for blood category i. Note that r', r'', p', p'', π_p', π_c', π_r', etc., are assumed independent of blood type. Note that $\lambda_i'' = 0$ unless we are concerned with the day prior to a scheduled surgery day. Circular nodes denote chance forks while square nodes denote decision forks. Parameters emanating from a decision fork will be called "decision parameters."

indicated by the presence or absence respectively of the symbol ^ over the parameter. Thus $\hat{\pi}''_c$ = the conditional probability, given a scheduled special surgery requiring blood constituents, that the demand is for cryoprecipitate.

and $\hat{p}'$ = the conditional probability, given an emergency-special surgery, that whole blood is chosen by the manager.

Clearly probabilities such as p' and p'' are functions of the managers policy and criteria.

Two typical branches from Figure 4 are extended to completion in Figure 5. We emphasize that such a decision tree is really most essential for a simulation study where a detailed breakdown is necessary.

4.2. Estimation of Parameters

Estimating the parameters shown in Figures 4 and 5 is a burdensome task confounded further by the decision parameters' dependence both on current inventory levels as well as the policy of the blood bank manager at a given point in time. To illustrate, a preference for the use of red cells may give way to the use of whole blood at times when the supply of red cells is low. Furthermore, it must be emphasized that the decision parameters in Figures 4 and 5 depend heavily on whether or not there is a freezer-system in the blood bank; so that we must estimate these parameters separately for the two cases.

In the case where there is no freezer-system, we may estimate both the decision and demand parameters from past performance of the blood bank. In cases where data is sparce, it is an easy matter to obtain rough estimates of some of the parameters and verify the simulation results by sensitivity analyses. When a freezer-system is in operation, all the decision parameters must be re-estimated to reflect the revised policy of the bank and hospital staff. We must in this case rely more heavily on subjective judgments with a subsequent sensitivity analysis.

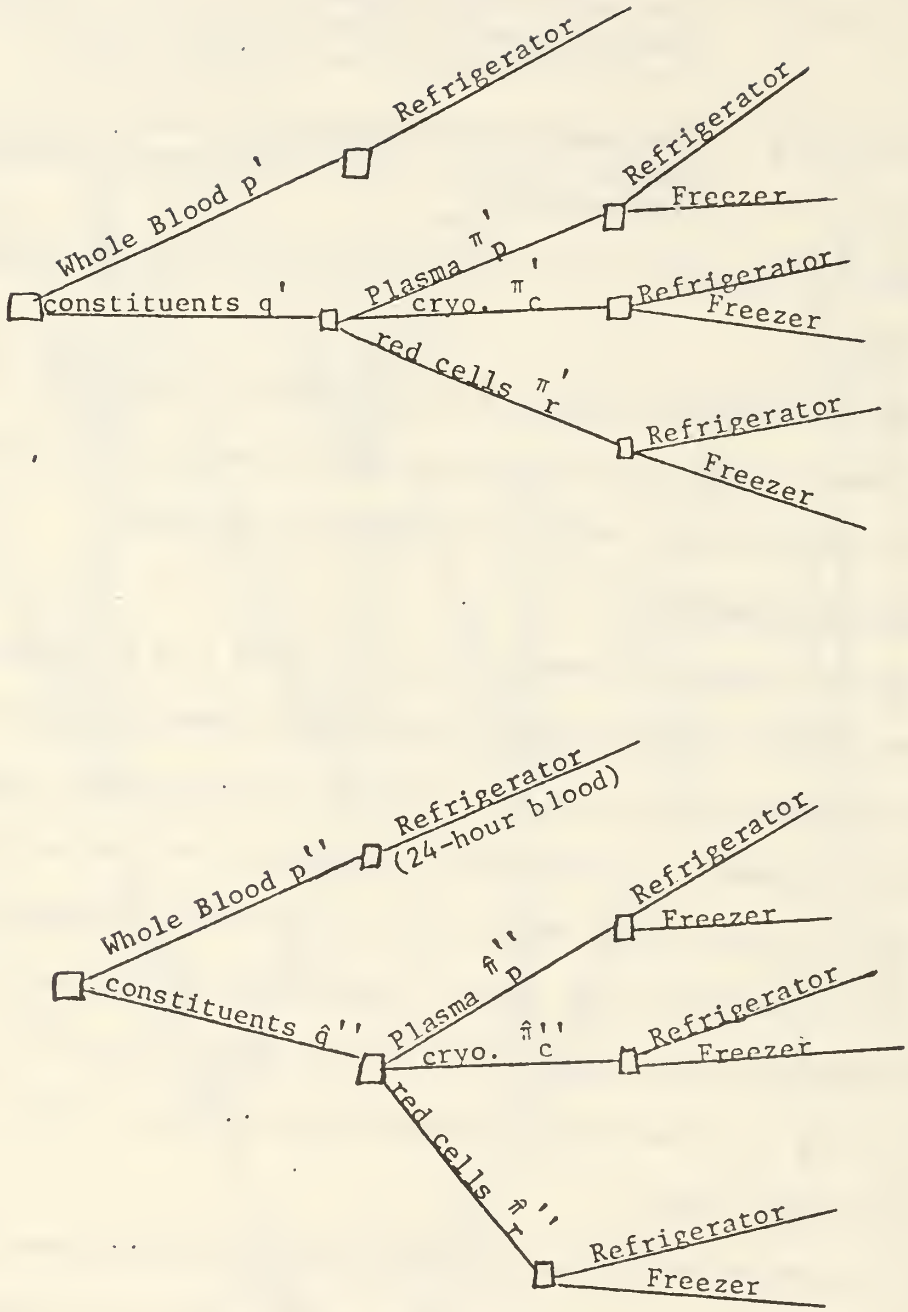

FIGURE 5. Extension of two typical branches from decision tree in Figure 4. Note that the special surgery indicated in the second branch results in use of 24-hour blood in lieu of the modified FIFO policy used in general.

4.3. Model of Inventory Management

We shall assume, when there is no freezer system, that the manager uses simple "order-up-to" policies for each blood category, summarized by eight critical levels $(Q_i, i=1,2,...,8)$ for whole blood. We also assume that there are eight such critical levels for each of the primary blood constituents, and that the manager orders whole blood to be sent to the centrifuge when any one of these constituents falls below its critical level.

When a freezer system is introduced, we must modify all of the above critical levels in recognition of the freezer's presence. In addition to including minimum critical levels for the freezer, we must also include maximum level constraints due to the freezer's limited capacity. The latter point is not trivial since from Figure 3 we see that the temptation is to route all 10 day old blood into the freezer to prevent expiration.

Once all of these critical levels are approximated and all decision and demand parameters estimated, we will then be able to compare the main features of each system -- with and without freezer -- be simulating demand and inventory regulation over the long haul. These main features once again are cost, wastage and shortage.

By specifically having identified the multifaceted nature of the demand for blood, and the complex inventory regulation process, we have also quite fully explained the procedural steps in the simulation study, to be discussed in section 5.

5. Computer Simulation.

The General Purpose Simulation System was selected because of its inherent first-in-first-out (FIFO) treatment of transactions and because of the natural analogs existing between its built-in entities such as queues and storages.

The model was constructed to provide information for a single category of blood at a time. The results to follow are for blood category O+ only. Information regarding other categories can be obtained by simply altering the input parameters. The simulation is conducted with one minute as the standard unit of time, and an iteration is of five-hundred days duration for each inventory policy investigated.

Tables II and III summarize the parameter values derived from data (or hypothesized) for this first run.

TABLE II.

Rates of Request for Blood Units
(Estimated from Hospital Data)

Category	Rate	Number/Day	Approximate percentage of total rate
1	λ_1	2.50	36
2	λ_2	2.114	31
3	λ_3	.543	8
4	λ_4	.671	10
5	λ_5	.595	9
6	λ_6	.185	3
7	λ_7	.158	2
8	λ_8	.109	1

TABLE III.

Other System Parameters
(Hypothesized Subjectively)

Parameter	Value
$p' = p''$	.50
$q'' = q''$	.50
$\pi'_p = \pi''_p$	.15
$\pi'_c = \pi''_c$	.15
$\pi'_r = \pi''_r$	.20
$\theta \equiv \lambda'_i/\lambda_i$	.10

Figures 6 and 7 graphically represent a comparison of expiration and shortages between the single and dual (i.e. without and with freezer) systems, for a given simulation run. What becomes clear qualitatively is that at low inventory levels the freezer-system is markedly superior at preventing shortages and only mildly superior at preventing expirations. Also, at high inventory levels, the freezer system is markedly superior at preventing expirations and moderately so at preventing shortages. In the mid range of inventory levels, there is a more than moderate superiority on both counts.

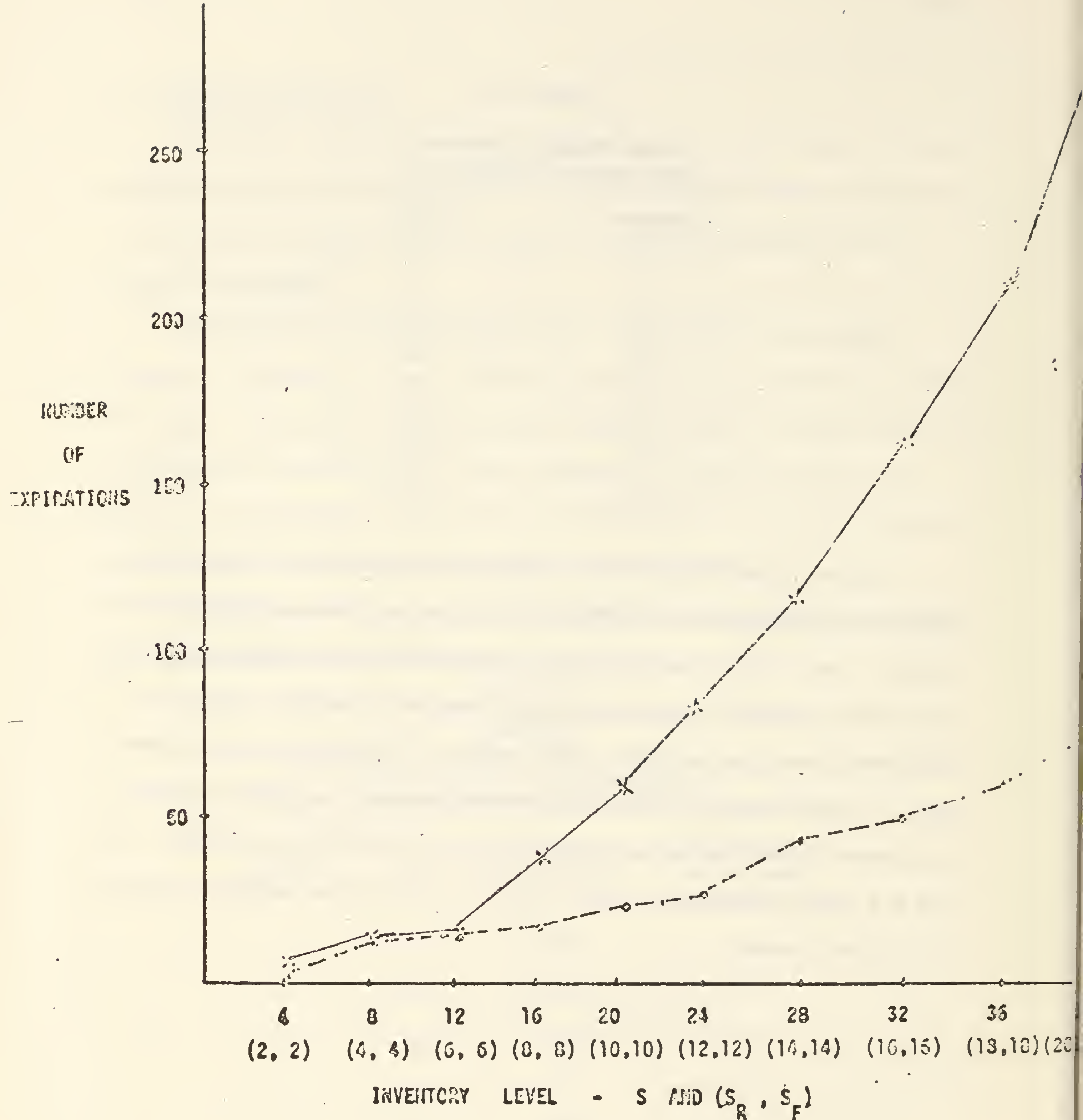

Figure 6.

(S_R,S_F) represents the order-up-to-level for the refrigerator and freezer, respectively.

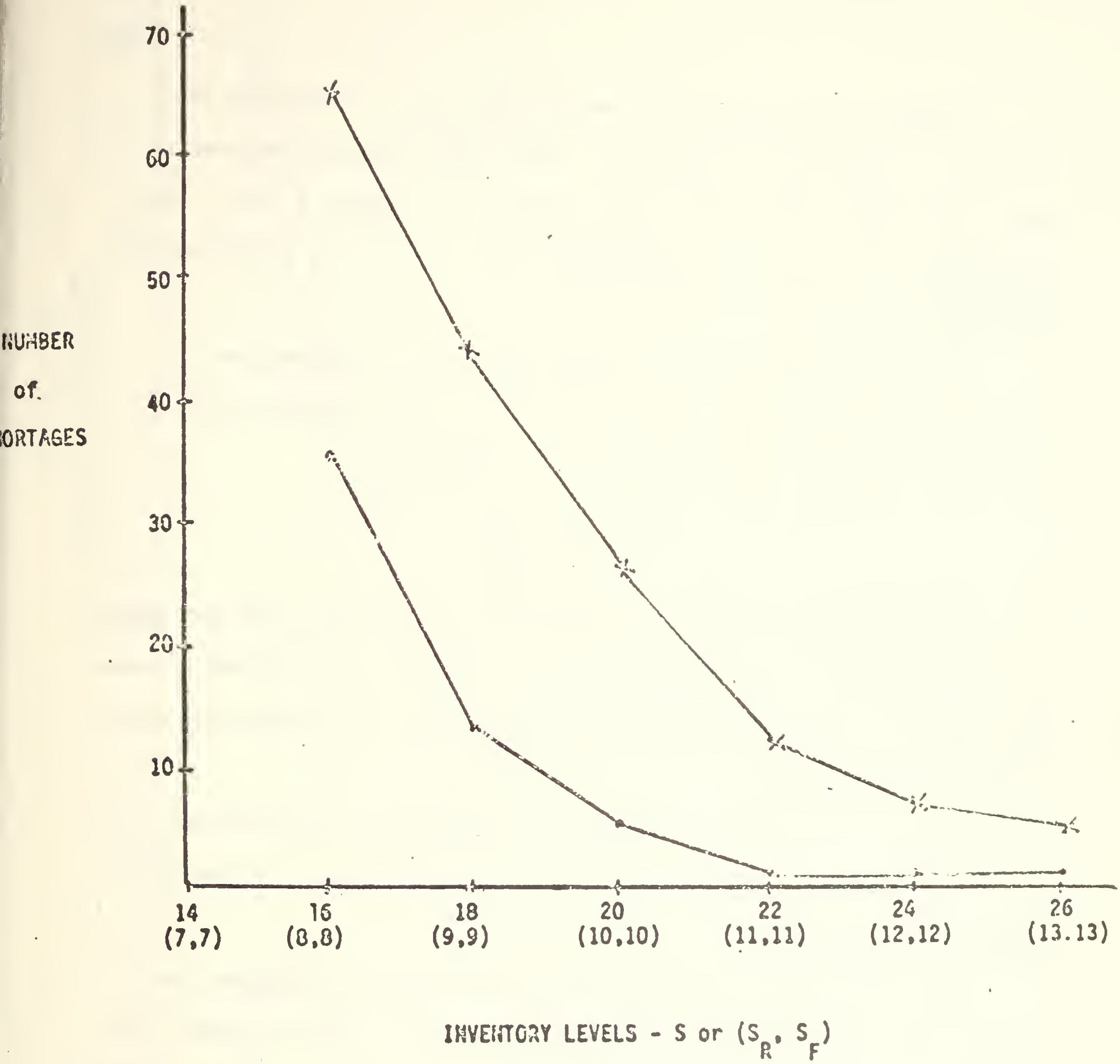
NUMBER
of
SHORTAGES
70
60
50
40
30
20
10
14
(7,7)
16
(8,8)
18
(9,9)
20
(10,10)
22
(11,11)
24
(12,12)
26
(13.13)
INVENTORY LEVELS - S or (S_R, S_F)

Figure 7.

To verify these results, we ran 30 realizations of 500 days each for both the single and dual system. The results in every realization bore out the same qualitative results depicted in Figures 6 and 7. The differences in shortages and expirations were in all cases significantly different from zero.

Figure 8 presents confidence bands for the mean differences in shortages and expirations. More explicitly, at each inventory level (S versus (S_R, S_F)) the 95% confidence interval is

$$\bar{D} \pm 2.045 \frac{S_D}{\sqrt{30}} ,$$

where $\bar{D}$ represents the average difference between single and dual system, S_D represents the sample standard deviation of the set of 30 differences, and where 2.045 is the 2.5% critical value for the t distribution with 29 degrees of freedom.

Note that each graph represents nine confidence intervals and is not a simultaneous confidence band. The values employed in Figure 8 are summarized in Table IV.

The conclusions to be drawn are qualitatively no different from those mentioned upon inspection of Figures 6 and 7. However, these now have some statistical muscle.

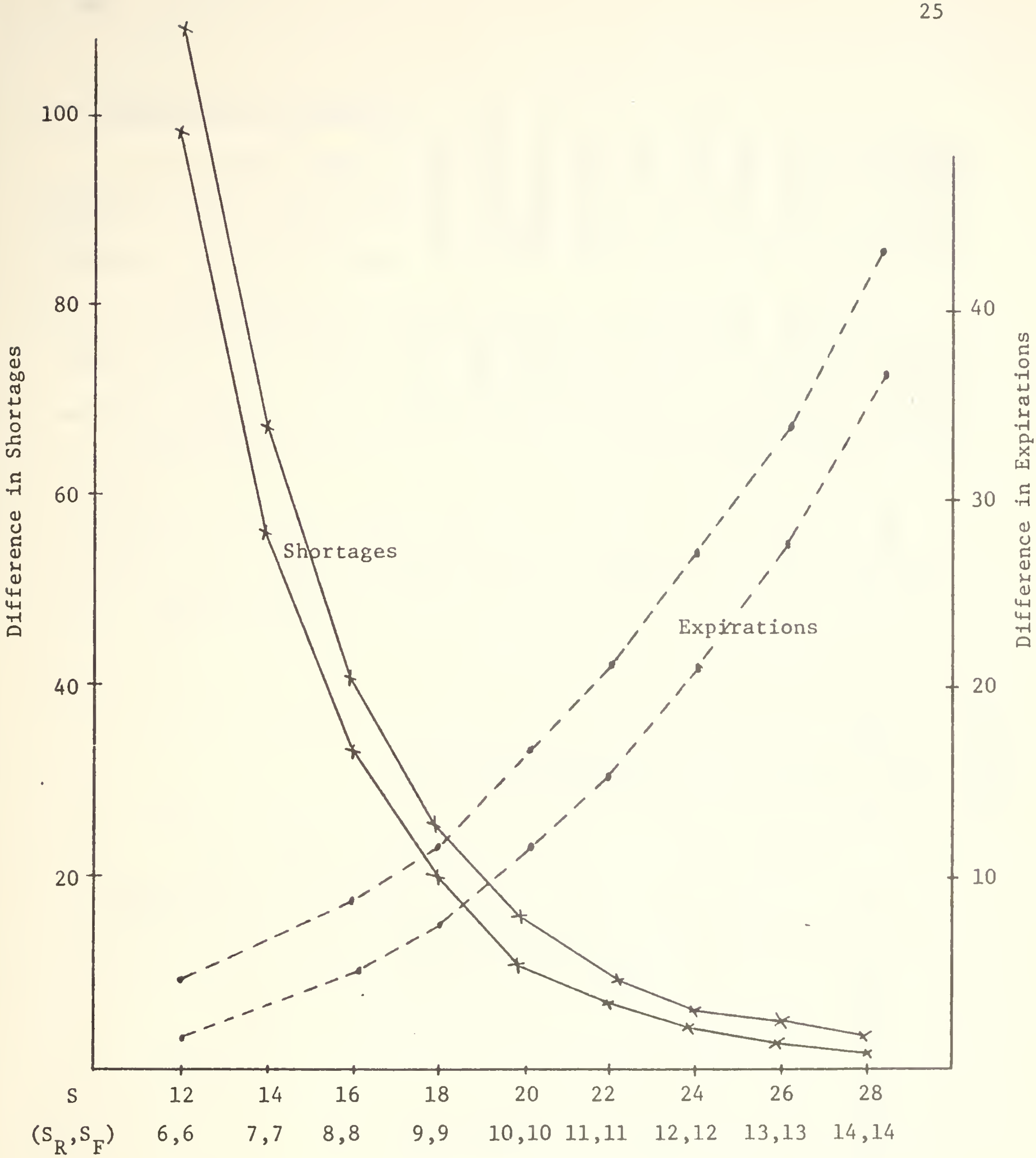

FIGURE 8.

Confidence Band for Mean Difference in Shortages and Expirations Between Single and Dual System

TABLE IV.

S	(S_R,S_F)	$\bar{D}$ (Shortages)	$\bar{D}$ (Expirations)	S_D (Shortages)	S_D (Expirations)	Confidence Interval (Shortages)	Confidence Interval (Expirations)
12	(6,6)	103.73	3.07	15.58	3.69	(97.92,109.55)	(1.69,4.45)
14	(7,7)	61.52	4.84	12.87	4.18	(56.72,66.33)	(3.28,6.40)
16	(8,8)	36.9	6.63	9.33	5.07	(33.42,40.38)	(4.74,8.52)
18	(9,9)	22.43	9.67	6.60	5.76	(19.97,24.89)	(7.52,11.82)
20	(10,10)	13.17	13.9	6.24	6.60	(10.8,15.5)	(11.4,16.4)
22	(11,11)	8.27	17.9	4.39	7.44	(6.6,9.9)	(15.1,20.7)
24	(12,12)	5.33	23.9	2.91	8.4	(4.2,6.4)	(20.8,27.0)
26	(13,13)	3.9	30.8	2.56	8.1	(2.9,4.9)	(27.8,33.8)
28	(14,14)	3.2	39.73	1.81	9.7	(2.5,3.9)	(36.1,43.4)

6. Conclusions and Summary.

It is rather clear from Figure 8 that the effects of a centrifuge-freezer system can be profound regardless of the inventory policies followed at the blood bank. Further consideration could be given to a sensitivity analysis relating differences in shortages and expirations to departures in the values of the parameters in Table III. Such a sensitivity analysis could be used in a cost-benefit analysis to determine the range of potential benefits of a dual system for various inventory policies. Finally, such a study could dramatically affect the policy followed by the blood bank manager, the actual effects depending upon the individual needs and peculiarities of the blood bank.

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